

Variable stars in the field and in the clusters of the Fornax dwarf spheroidal galaxy

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Abstract. We present the first results of a variable star search in the field and in the globular clusters of the Fornax dwarf spheroidal galaxy. Variable stars were identified using the Image Subtraction Technique (Alard 2000) on time-series data obtained with the ESO 2.2 m and the Magellan 6.5 m telescopes. The variable star sample includes RR Lyrae stars, Dwarf Cepheids and Anomalous Cepheids. The pulsation properties (namely: periods, light curves, period-amplitude relations and classification in Oosterhoff types) of Fornax variables from the present study are discussed in some detail.

1. Why to study the variable stars in an external galaxy?

Pulsating variable stars such as RR Lyrae stars, Dwarf Cepheids and Anomalous Cepheids are very interesting astronomical objects that can be used to derive important information on the stellar system they belong to. They can be easily identified, even in high crowding conditions, thanks to their light variation, and their periods are independent from reddening and distance. Variable stars are good tracers of the different stellar generations in a galaxy; in particular

the RR Lyrae stars trace the oldest population, and the Anomalous Cepheids the intermediate age populations, allowing one to identify different star formation episodes that have occurred in the host stellar systems. Variable stars are also *standard candles* and can be used to measure distances: the RR Lyrae stars through their nearly constant absolute magnitude in the V band, and the Cepheids because they obey a *period-luminosity relation*. Being among the oldest stars in a galaxy the RR Lyrae stars witnessed the first epochs of the galaxy formation, thus they provide information on the galaxy formation mechanism and assembling (Catelan 2004; Clementini et al. 2004) .

We have made a comprehensive and deep study of the short period variable stars in the Fornax dwarf spheroidal galaxy (dSph) mapping its classical instability strip from the Dwarf Cepheids ($V \sim 24\text{--}25$ mag) up to the Anomalous Cepheids ($V \sim 19$ mag) in the field and in the globular cluster (GC) system of the galaxy, using wide field imaging obtained with the mosaics of the 2.2 m ESO-MPI and the 4 m Blanco CTIO telescopes, and deep, high spatial resolution photometry of the clusters taken with the 6.5 m Magellan/Clay telescope. Here, we report preliminary results from the analysis of the data covering a northern portion of the Fornax galaxy, along with results on its clusters 2, 3, 4, and 5.

2. Fornax dSph

Fornax is a dwarf spheroidal galaxy placed at about 140 kpc from the Milky Way. The galaxy color-magnitude diagram (CMD) shows the presence of an old, an intermediate and a young stellar population (Buonanno et al. 1985, Stetson, Hesser, & Smecker-Hane 1998, Saviane, Held, & Bertelli 2000). Fornax, Sagittarius and, possibly, the newly discovered Canis Major, are the only dwarf spheroidal galaxies known to contain globular clusters. The Fornax GC system is formed by five clusters (Baade & Hubble 1939; Hodge 1961, 1965, 1969). Previous photometric studies of Fornax GCs show that their HB morphologies are consistent with the presence of RR Lyrae stars (Buonanno et al. 1998, 1999). This offers a great opportunity to investigate the variable star populations in extragalactic globular clusters, and to compare their properties with those of the field variables in Fornax and in the Milky Way field and clusters.

One of the most intriguing properties of the variable stars in the Galactic GCs is the Oosterhoff dichotomy (Oosterhoff, 1939): a sharp subdivision into two distinct types, named Oosterhoff type I (OoI) and II (OoII), respectively, according to the mean periods of the *ab*-type RR Lyrae stars (OoI: $\langle P_{ab} \rangle = 0.55$ d, OoII: $\langle P_{ab} \rangle = 0.65$ d). Do extragalactic globular clusters such as those in Fornax and the galaxy field variables conform to the Oosterhoff dichotomy observed in the Milky Way?

Bersier & Wood (2002) made the first search for variables in the field of Fornax and identified 515 candidate RR Lyrae stars, on an area of about 0.5 deg^2 covering the central region of the galaxy. They concluded that the field RR Lyrae stars in Fornax have properties intermediate between the two Oosterhoff types. However, since the magnitude of the RR Lyrae stars is close to the detection limit of their photometry, and because their data are not good enough

to determine the type of variable on the basis of the light curve their analysis needs to be confirmed by better photometric data.

Mackey & Gilmore (2003, hereafter MG03) identified candidate RR Lyrae stars in four of the Fornax globular clusters (namely Fornax 1, 2, 3 and 5) using HST archive data. Due to the short observational baseline and the small number of frames their data were not adequate for a period search. Therefore, they determined periodicities by fitting template RR Lyrae light curves to their data, and found that Fornax clusters possess mean characteristics intermediate between the two Oosterhoff groups. Again, these results need to be confirmed on the basis of accurate and well sampled light curves allowing independent estimates of the periods. Our survey also allowed the first variability study of Fornax 4, the cluster in the central region of Fornax dSph.

3. Data acquisition and reduction strategies

We collected B, V time-series data of Fornax with three different telescopes and instruments, namely the wide field imager of the 2.2 m ESO-MPI telescope, the mosaic of the 4 m Blanco CTIO telescope, and the Magic camera of the 6.5 m Magellan/Clay telescope. Observations span the time interval from November 2001 to December 2004. Central coordinates and field of view (FOV) of our pointings of Fornax dSph are summarized in Table 1, along with the number of frames per photometric band obtained at each pointing. Photometric reduc-

Table 1. Photometric data of Fornax dSph.

Telescope & Instrum.	FOV	Target	α_{2000}	δ_{2000}	N_V	N_B
2.2 m ESO WFI	$33' \times 34'$	Field_1(For 3)	$02^h 39^m 59^s$	$-34^\circ 10' 00''$	17	61
2.2 m ESO WFI	$33' \times 34'$	Field_2(For 2,4)	$02^h 39^m 45^s$	$-34^\circ 39' 00''$	16	59
4 m CTIO WFI	$36' \times 36'$	Field_A(For 4,5)	$02^h 41^m 05^s$	$-34^\circ 17' 30''$	145	64
4 m CTIO WFI	$36' \times 36'$	Field_B(For 2,3,4)	$02^h 39^m 24^s$	$-34^\circ 33' 16''$	16	8
6.5 m Magellan/Clay	$2.4' \times 2.4'$	For 2	$2^h 38^m 44.2^s$	$-34^\circ 48' 33.1''$	18	6
6.5 m Magellan/Clay	$2.4' \times 2.4'$	For 3	$2^h 39^m 46.7^s$	$-34^\circ 15' 23.1''$	5	5
6.5 m Magellan/Clay	$2.4' \times 2.4'$	For 4	$2^h 40^m 07.7^s$	$-34^\circ 32' 16.2''$	58	20
6.5 m Magellan/Clay	$2.4' \times 2.4'$	For 5	$2^h 42^m 21.3^s$	$-34^\circ 06' 05.2''$	56	20

tions have been completed for Field_1 and for all the Magellan fields. They were carried out with the packages DAOPHOT-ALLSTAR II (Stetson 1996) and ALLFRAME (Stetson 1994). Variable stars were identified using the Image Subtraction Technique as performed within the package ISIS2.1 (Alard 2000). This method is demonstrated to be very effective and allowed us to detect large numbers of bright variables as well as low-amplitude, faint variable stars such as the Dwarf Cepheids (DCs). These variables are about two magnitudes fainter than the RR Lyrae stars. So far, our sample of DCs in Fornax is the largest one in an extragalactic stellar system.

Here we present preliminary results from the analysis of the variable stars detected in the four lower chips of the mosaic of eight CCDs covering Fornax Field_1 (Section 4), and in four Fornax globular clusters (Section 5).

Figure 1. Color-magnitude diagrams of the four lower CCDs covering Fornax Field_1. Confirmed pulsating variable stars in Chip 6 and 7 (upper two panels of the figure) are marked by different filled symbols: Dwarf Cepheids (filled triangles, in yellow in the electronic edition of the paper); RR Lyrae stars (filled circles, red: single mode pulsators, blue: double mode pulsators); and Anomalous Cepheids (filled squares, green). Filled circles in the two lower panels of the figure are candidate variable stars detected in Chip 5 and 8, which still need to be confirmed and classified.

4. Fornax Field_1

Fornax Field_1 covers a $33' \times 34'$ area North of Fornax dSph center, with the regions of higher stellar density found in Chip 6 and 7 of the mosaic, and cluster Fornax 3 also falling in Chip 6. Figure 1 shows the CMDs of the lower four CCDs of Fornax Field_1, which cover an area of about 0.16 deg^2 , and are found to contain a total number of 706 candidate variable stars (displayed as large filled symbols). Study of the light curves, definition of the period, and classification

Table 2. Candidate variables in the lower four CCDs of Fornax Field_1.

CCD	RR Lyrae stars	ACs	DCs	Binaries	Total
Chip 6	110	11	23	15	159
Chip 7	137	—	23	15	175
Chip 5	—	—	7	—	209 ^a
Chip 8	—	—	14	—	163 ^a

^a The study of the light curves and the classification in types for the variables in Chip 5 and 8 is still in progress, only the DCs have been classified so far. Total numbers for these two chips may include spurious detections.

in types have been completed only for the variable stars in Chip 6 and 7. These confirmed variables are marked by different symbols in the two upper panels of Figure 1, namely: filled triangles are Dwarf Cepheids (DCs); filled circles are RR Lyrae stars; filled squares are Anomalous Cepheids (ACs). The filled circles in the two lower panels of Figure 1 are candidate variables that still need to be confirmed and classified; however, their position on the CMD is consistent with many of them being RR Lyrae stars and Dwarf Cepheids. Variable stars in the upper left panel of Figure 1 are plotted according to their intensity-averaged magnitudes and colors. They define very well the region of the classical instability strip in Fornax dSph. Candidate variables in the other panels of the figure span a much larger magnitude/color range because they are plotted at random phase. The number of candidate variables in each of the four CCDs analyzed so far and their classification in types, when available, are summarized in Table 2.

Table 3. Variable stars in Chip 6, divided by field and cluster For 3.

Target	RRab,c	RRd	ACs	DCs	Binaries
Field	72	10	9	21	15
For 3	18	10	2	2	-

We have already confirmed and classified in types 355 of the variable stars in Table 2. This number gives a lower limit for the variable star density in Fornax twice as much as that derived by Bersier & Wood (2002). In Table 3 we summarize results for Chip 6 dividing the variable stars between field and cluster. Figure 2 shows examples of light curves for the field (left panels)

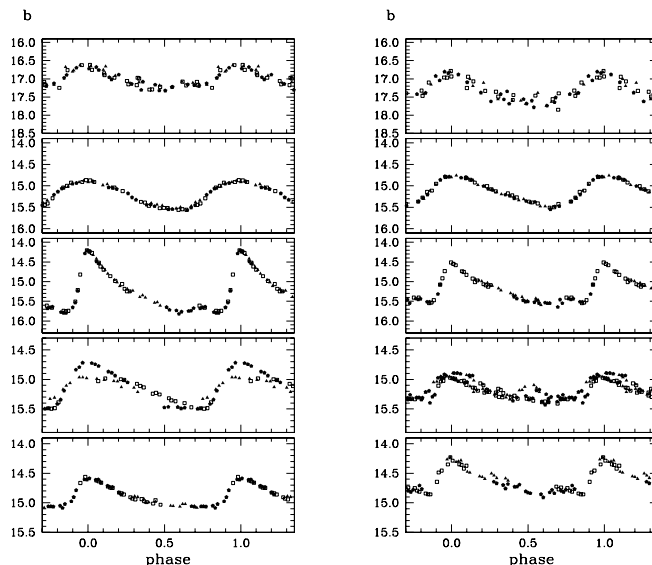


Figure 2. Instrumental B light-curves for variable stars in Chip 6. Left panels: field variables; right panels: variable stars in For 3. From top to bottom: DCs, c -, ab -, and d -type RR Lyrae stars, ACs.

and cluster (right panels) variable stars in this CCD. Variable stars in Chip 6 have been fully analyzed, and in the left panel of Figure 3 we plot their period-luminosity diagram in the V band. We can see how both Dwarf and Anomalous Cepheids follow a *period-luminosity relation*, while the RR Lyrae stars show a nearly constant average magnitude. The mean period of the field RR Lyrae stars in Chip 6 is 0.595 d (r.m.s.= 0.039), for the ab -type, and 0.361 d (r.m.s.= 0.040) for the c -type variables, respectively. These values confirm the intermediate Oosterhoff type of Fornax field RR Lyrae stars (see also right panel of Figure 3). We used the mean period of the ab -type RR Lyrae stars to estimate the metallicity of the old stellar population in Fornax. Adopt-

ing Sandage's (1993) relation $\log\langle P_{ab} \rangle = -0.092 [\text{Fe}/\text{H}] - 0.0389$ we obtain: $[\text{Fe}/\text{H}]_{\text{field}} = -1.78$. The average V magnitude of the field RR Lyrae stars in Chip 6 is: $\langle V(RR)_{\text{field}} \rangle = 21.281 \pm 0.100$ mag. This value leads to a distance modulus of: $\mu_{\text{Fornax}} = 20.72 \pm 0.10$ mag, (on the assumption of: $M_V(RR) = 0.50$ mag at $[\text{Fe}/\text{H}] = -1.5$, Gratton et al. 2003; $\Delta M_V(RR)/[\text{Fe}/\text{H}] = 0.22$ mag/dex, Gratton et al. 2004; $E(B-V) = 0.04 \pm 0.03$, and the standard extinction law), in very good agreement with estimates by Buonanno et al. (1999), Saviane et al. (2000), and MG03.

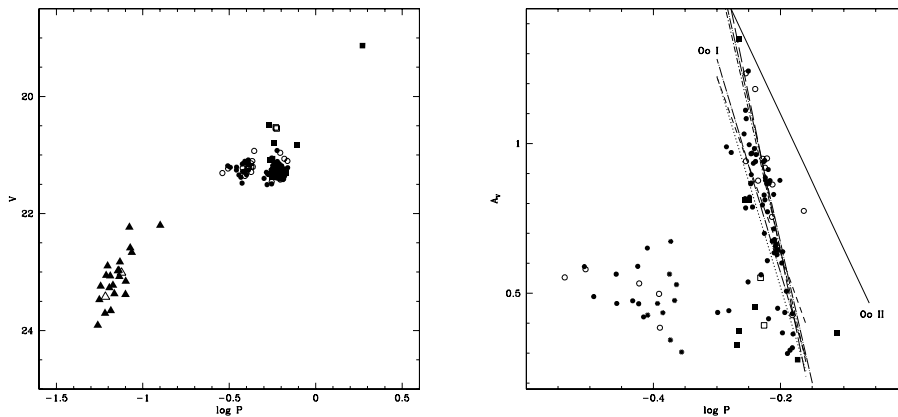


Figure 3. Period-Luminosity (on the left) and Period-Amplitude (on the right) relations in the V band for variable stars in Chip 6. Filled symbols are field variables, open symbols are variable stars in Fornax 3. Triangles are DCS, circles are RR Lyrae stars, squares are ACs. Lines in the right panel are the Period-Amplitude relations for OoI and OoII Galactic GCs from Clement & Rowe (2000; solid lines) and for some dwarf spheroidal galaxies: And VI (dotted line); Sculptor (short-dashed line); Leo II (long-dashed line); Draco (dotted-dashed lines) from Pritzl et al. (2002); and Leo I (dotted-long-dashed line) from Held et al. (2001).

5. Variable stars in Fornax globular clusters

Figure 4. Color-magnitude diagrams of Fornax GCs 3,4,5, and 2 from the ESO-WFI data (Fornax 3) and the Magellan/Clay observations (Fornax 2, 4 and 5). Variable stars are marked by solid symbols, as in Figure 1.

Well sampled light curves were obtained for the variables in Fornax 3, 5 and 4. Variable stars were identified also in Fornax 2, however data for this cluster do not allow a reliable definition of the periods. Results obtained for the four clusters are summarized in Table 4. The average periods of the ab -type RR Lyrae stars in Fornax 3 and 5 are in good agreement with the values derived by MG03 for their subsamples of RRab's with good periods. Our $\langle P_c \rangle$ values

Table 4. Results on the variable stars in Fornax clusters 2, 3, 4, and 5.

Cluster	RR Lyrae stars	DCs	ACs	$\langle P_{ab} \rangle$	$\langle P_c \rangle$	[Fe/H] ^a
For 3	28(13ab,5c,10d)	2	2	0.606	0.358	−1.96
For 4	18(14ab,3c,1d)	-	-	0.592	0.359	−2.01
For 5	17(9ab,7c,1d)	1	-	0.576	0.353	−2.20
For 2	10	-	-	-	-	−1.79

^aMetal abundances are from Buonanno et al. (1998,1999)

are instead shorter than in MG03. This is particularly true of For 3, the cluster where we also detected a large population of double mode pulsators, twice in number the cluster RRc variables. This type was not recognized by MG03 and may have contaminated their RRc sample. These authors also found in For 3 several very long-period RRc's, that we did not find in our period search.

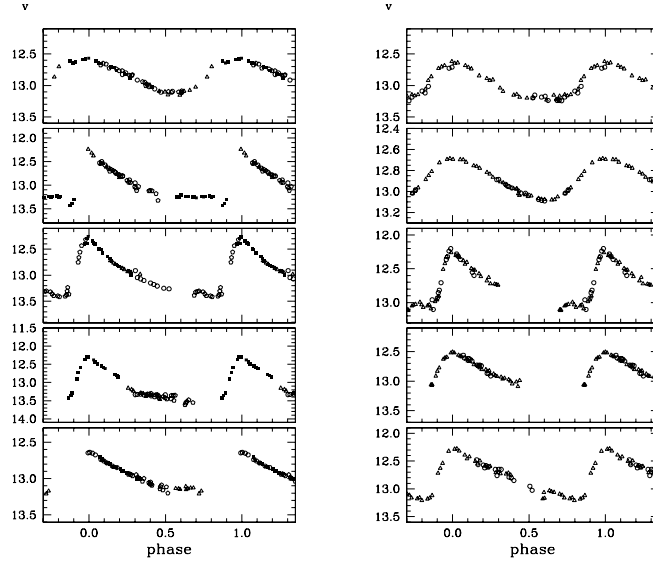


Figure 5. Instrumental *V* light-curves for *ab*- and *c*-type RR Lyrae stars in Fornax clusters 4 (left panels) and 5 (right panels).

Figure 4 shows the CMDs of the four clusters with the variable stars marked by filled symbols. Examples of light curves of *ab*- and *c*-type RR Lyrae stars in For 4 and 5 are shown in Figure 5. Using the average periods of the *ab*-type RR Lyrae stars derived in our study for the variables in For 3, 4 and 5 we can now check the location of Fornax GCs in the Oosterhoff diagram, showing the relationship between the average period of *ab*-type RR Lyrae stars and the metallicity. This is shown in Figure 6. We find that Fornax 3 falls slightly below the edge of the Oosterhoff II region, while Fornax 5 is at the edge of the OoI

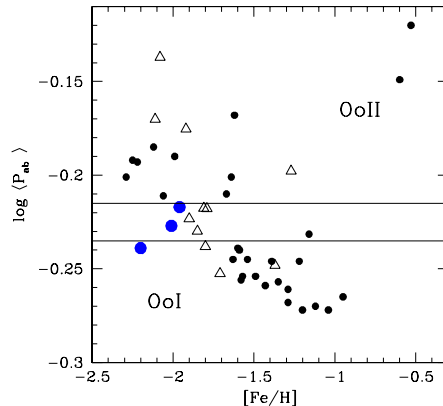


Figure 6. Position occupied in the Oosterhoff plane by the Galactic GCs (dots; from Castellani, Caputo, & Castellani 2003), the Large Magellanic Cloud clusters (triangles), and Fornax clusters For 3, 4 and 5 (big circles, in blue in the electronic edition of the journal; from the present study).

region. Fornax 4 with $\langle P_{ab} \rangle = 0.59$ d falls inside the “Oosterhoff gap”. However, this cluster shows two separate peaks in the period distribution of the *ab*-type RR Lyrae stars, with average values respectively around 0.55 and 0.65 d, as if, similarly to NGC1835 in the LMC (Soszynski et al. 2003), there is an Oosterhoff dichotomy within the cluster itself.

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